PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : G01J 3/18	A1	(11) International Publication Number: WO 90/02928 (43) International Publication Date: 22 March 1990 (22.03.90)

(21) International Application Number: PCT/GB89/01035

(22) International Filing Date: 5 September 1989 (05.09.89)

(30) Priority data:
8821029.9 7 September 1988 (07.09.88) GB

(71) Applicant *(for all designated States except US)*: SIRA LIMITED [GB/GB]; South Hill, Chislehurst, Kent BR7 5EH (GB).

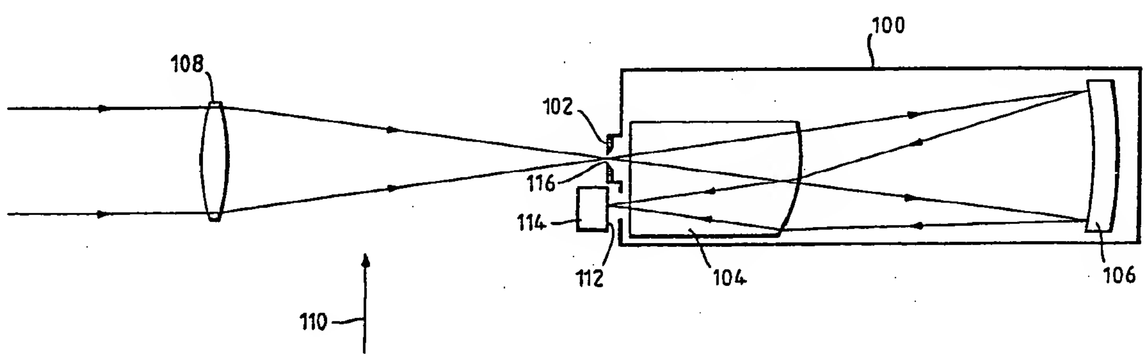
(72) Inventor; and
(75) Inventor/Applicant *(for US only)* : LOBB, Richard, Daniel [GB/GB]; 25 Marlings Park Avenue, Chislehurst, Kent BR7 6QN (GB).

(74) Agent: WRIGHT, Hugh, Ronald; Brookes & Martin, 52/54 High Holborn, London WC1V 6SE (GB).

(81) Designated States: AT (European patent), BE (European patent), CH (European patent), DE (European patent), FR (European patent), GB (European patent), IT (European patent), LU (European patent), NL (European patent), NO, SE (European patent), US.

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: IMAGING SPECTROMETER



(57) Abstract

A spectrometer in the form of an imaging spectrometer for measuring the spectral distribution of target surfaces as a function of position on the surface, comprising an object plane (102), corrector means (104), a curved reflecting grating (106), and an image plane (112), whereby radiation from the object plane (102), on which the image of the target surface may be focused, passes to the corrector means (104) and from the corrector means (104) to the curved reflecting grating (106), is reflected therefrom to the corrector means (104) and passes from the corrector means (104) to the image plane where a camera or photo detector may be mounted.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria
AU	Australia
BB	Barbados
BE	Belgium
BF	Burkina Fasso
BG	Bulgaria
BJ	Benin
BR	Brazil
CA	Canada
CF	Central African Republic
CG	Congo
CH	Switzerland
CM	Cameroon
DE	Germany, Federal Republic of
DK	Denmark
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
HU	Hungary
IT	Italy
JP	Japan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
LI	Liechtenstein
LK	Sri Lanka
LU	Luxembourg
MC	Monaco
MG	Madagascar
ML	Mali
MR	Mauritania
MW	Malawi
NL	Netherlands
NO	Norway
RO	Romania
SD	Sudan
SE	Sweden
SN	Senegal
SU	Soviet Union
TD	Chad
TG	Togo
US	United States of America

IMAGING SPECTROMETER

The present invention relates to a spectrometer.

Spectrometers are instruments used to record spectral distributions of radiation sources. Typically, radiation from the source is focused onto a slit aperture, called the entrance slit. The radiation passing through the slit is collimated by a lens or concave mirror and passed to a dispersing element.

The dispersing element, a diffraction grating or a prism of glass or other refracting material, produces different angular deflections for different wavelength components of the radiation beam. The dispersed collimated beam is then focused by a lens or concave mirror to form a spectrum image. The dispersing element is usually oriented to spread the radiation spectrally in the direction orthogonal to the slit. For optimum spectral resolution, the spectrum is an image of the entrance slit, with good resolution of the slit jaws in each radiation wavelength.

It is not generally necessary to achieve good imaging at the spectrum of structure orthogonal to the entrance slit jaws. Some astigmatism in the spectrometer optics (difference of focus for orthogonal sets of lines in the image) is generally acceptable.

The spectrum image can be recorded on photographic film. Alternatively, TV camera target can record the spectrum image, or the spectrum image can be scanned by a slit and photodetector, to record the image as an electrical signal.

Imaging spectrometers are spectrometers designed to measure the spectral distribution of target surfaces as a function of position on the surfaces. Typically, an image of a target area is formed on a slit-shaped spectrometer entrance aperture at the spectrometer object plane, and a slit-shaped area of the target surface is sampled. Points along the slit-shaped area are imaged as line spectra in the spectrometer spectrum plane. An arrangement of this kind, typically with a TV camera recording the spectrum image, can be used to measure the spectral distribution of many points simultaneously along the sampled line. The line may be scanned orthogonal to its length by a scanning mechanism or by relative movement between the object and the spectrometer, allowing a set of lines on the target surface to be sampled in sequence.

Here complex entrance apertures may be used, each imaged in the spectrometer spectrum plane, to provide increased radiant flux throughput.

If the image of the target surface formed at the spectrometer object surface has well-defined structure, it is not essential to include an aperture.

Imaging spectrometers are used for example to measure the spectral distribution of the Earth's surface radiance from an aircraft or satellite as a function of position on Earth. The fine spectral resolution of a spectrometer can be used for example to detect fluorescence from oceanic organisms, and hence measure biological activity. Land colour measurements are used for example for identification of vegetation.

As in all spectrometers, good imaging at the spectrum

of structure in the object plane orthogonal to the dispersion direction is necessary for spectral resolution. In imaging spectrometers, spatial resolution is also required, so that there is a need for good reimaging, at the spectrum, of structure in the object plane parallel to the dispersion direction. Imaging spectrometers are therefore distinguished from other spectrometers in requiring good correction for astigmatism.

Correction of optical aberrations presents a significant problem in existing imaging spectrometer design forms. Aberration is generally introduced by the collimating and spectrum imaging components. If refracting components are used, the spectral range of the spectrometer is restricted by chromatic aberrations. Concave mirrors introduce no chromatic aberrations and are frequently used for collimation and spectrum imaging in systems covering a wide spectral range. But, since single mirrors must generally be used off axis, they can introduce unacceptable astigmatism.

Multiple mirror imaging system and catedioptric imaging systems can be considered for the collimation and spectrum imaging functions, but these arrangements present other serious problems, generally including an undesirable level of optical complexity. Two-mirror anastigmats are bulky. Systems of Cassegrain form, including catedioptric variants, suffer from central aperture obscurations at moderate field angles.

These problems can generally be alleviated by arranging for the collimating and spectrum imaging components to have long focal lengths. The reduced optical power of

the components reduces most optical imaging aberrations. However, this approach can lead to systems of excessive size, particularly for use in satellites or aircraft.

The present invention provides, a spectrometer comprising an object plane, corrector means, a curved reflecting grating, and an image plane, whereby radiation from the object plane passes to the corrector means, and from the corrector means to the curved reflecting grating, is reflected therefrom to the corrector means, and passes from the corrector means to the image plane.

Spectrometers embodying the invention will now be described by way of example only and with reference to the accompanying drawings in which:-

Figure 1 is a schematic diagram showing the optical configuration of a satellite-borne instrument using an imaging spectrometer to measure ocean colour from Earth orbit,

Figure 2 is a view of part of the instrument of Figure 1 orthoganal to the diffraction grating lines,

Figure 3 is a view of the part of the instrument shown in Figure 2 parallel with the diffraction grating lines,

Figure 4 shows an alternative arrangement of the instrument of Figures 1 to 3,

Figure 5 shows an alternative arrangement of the instrument Figure 1 utilising the reflective

components, and,

Figure 6 is an alternative arrangement of the instrument Figures 1 to 3.

The spectrometer, 100 in Figure 1, is an optical system comprising an entrance aperture 116 at an object plane 102 initiated by a dashed line, a refracting corrector 104, and a concave reflecting diffraction grating 106.

The system in which the spectrometer is used may be an instrument as indicated in Figure 1, designed to be carried on an Earth-orbiting satellite or an aircraft, and used to measure the spatial and spectral radiance distributions of ocean and land.

Figure 1 shows an Earth-imaging lens, 108, which forms an image of the object to be measured, in this case the Earth's surface, onto the object plane 102. The movement of the satellite with respect to Earth, indicated in Figure 1 by the arrow 110, scans the Earth image across the entrance aperture at the object plane, so that a wide swath of Earth surface is measured on each satellite orbit.

The spectrometer forms a spectrum image at the spectrum plane 112. In the instrument shown in Figure 1, a CCD area array detector 114 is located with its photosensitive surface at the spectrum plane 112. The CCD output signals can be processed and transmitted to Earth by the satellite communications system, and used on Earth to provide detailed spatial and spectral data on ocean and land radiance distributions.

The spectrometer optical design is shown in detail in

Figures 2 and 3. Figure 2 shows a section orthogonal to the rulings on the diffracting surface 200 of the concave diffraction grating 106. The slit shaped aperture is parallel to the grating rulings.

The object plane 102 is at or near the spectrum plane 112. The diffraction grating surface is spherical, with a centre of curvature 202 at or near the spectrum plane 112. The corrector transmits wavelengths for which the system is designed, with a mean refractive index n. The refractive corrector has a flat surface 204 close to the object plane and the spectrum plane, and a spherical surface 206 concentric with the diffraction grating. The radius of curvature Rc of the spherical surface of the refracting corrector and the radius of curvature Rg of the grating are approximately related by the formula:

$$n.Rc = (n-1).Rg$$

The grating rulings are parallel and equi-spaced in their projection on the osculating plane 208 which is tangential to the grating at the nominal optical axis of the system, 210.

Figure 3 shows the same optical system as Figure 2, but in a view orthogonal to the grating rulings. Rays are shown travelling from one end of the entrance aperture 116, to the spectrum image plane, 112.

Correction of primary optical imaging aberrations is almost perfect in this apparatus. The flat face 204 of the corrector, 104, is close to the object plane and spectrum image plane and can introduce little aberration of any kind. Location of the centre of curvature of the grating and the spherical surface of

the corrector near the object plane and spectrum plane ensures correction at these surfaces of spherical aberration, coma and axial chromatic aberration. Symmetry about the axial plane orthogonal to the grating rulings ensures correction of transverse chromatic aberration in the section parallel with grating rulings (which would otherwise introduce tilt or curvature of line spectra).

Transverse chromatic aberration is not corrected in the section orthogonal to the grating rulings, but this merely modifies the mapping of wavelengths in the spectrum plane in this section. The residual transverse chromatic aberration in the section orthogonal to the grating rulings is constant in the section parallel with the grating rulings, so that no slit image curvature is introduced by chromatic aberration of the refracting component.

The concave diffraction grating introduces astigmatism and field curvature in the diffracted spectrum image. But if the above formula is used to select the curvature of the spherical surface of the corrector, this surface corrects the primary astigmatism and field curvature introduced by the concave grating, for a range of wavelenths and for all points in the plane of the entrance aperture. This primary correction is independent of the refractive index of the corrector, 104, so that in principal any homogeneous materials, which is transparent to the radiation to be measured, is suitable for the corrector, 104.

It is not essential for the entrance aperture to be slit shaped, though this is often convenient for spectral and spatial analysis. More complex aperture

shapes, including two or more slits, may be used.

In principle, spectral analysis can be carried out with no aperture at the object plane 102, if the image formed at the object plane has structure.

The spatial and spectral resolution of the system is limited by higher order astigmatism, varying with the fourth and higher even orders of the off-axis distances of points in the object plane and spectrum plane. This higher order aberration is minimised by selecting a refractive index for the corrector as close as possible to 2. For the visible and near infrared spectral regions, moderately high index optical glasses can reasonably be considered. We proposed to use Schott glass F2 for the spectral range from 400nm to the near infrared, giving high transmission over this region. Fused quartz is a suitable choice for work from the near ulta-violet to the near infrared. Several materials with indices over 2 could be considered for the infrared region, including zinc sulphide, zinc selenide and KRS5.

High order astigmatism introduced by the refractive corrector is compensated in optimised designs by reducing the primary correction introduced at the spherical surface. This adjustment is made by increasing the radius of curvature of the spherical surface of the corrector to a value larger than that given by the primary correction formula.

Data for a typical design is tabulated below.

	Surface	Curvature (mm)	Grating Period (mm)	Separation (mm)	Material	Refractive Index
1	(object plane)	0	-			
2		0	-	0.20	vacuum	1.0000
3		-0.01266	-	78.66	F2	1.6200
4	(grating)	-0.00500	0.00644	121.02	vacuum	1.0000
5		-0.01266	-	121.02	vacuum	1.0000
6		0	-	-78.66	F2	1.6200
7	(image plane)	0	-	-0.20	vacuum	1.0000

In the table, optical surfaces are given in the order in which radiation passes through them. The initial radiation path is left to right. Left-to-right separations are positive and right-left separations are negative. Negative curvatures imply that the centre of curvature is to the left of the surface. Curvatures are given as reciprocal radii of curvature. It will be appreciated that surfaces 5 and 3 are the same, and that surfaces 6 and 2 are the same. The refractive index given for Schott glass F2 is representative of visible wavelengths - the index varies as a function of wavelength.

The design of the appartus has been optimised assuming:

(a) that the centre of the entrance aperture is placed at the centre of curvature of the grating and of the spherical surface of the corrector,

(b) that the wavelength range is from 400mm to 1050mm,
(c) that the slit length is 17.33mm, and
(d) that the input beam numerical aperture is 0.2

The formula for the corrector curvature which provides primary field curvature and astigmatism correction also places the grating at the focal plane of the corrector. The pupil of the optical system is located at the grating, as is normal in spectrometer systems, so that the system is telecentric (has a pupil at a large distance) in the spaces of both the object plane and the spectrum image.

Telecentricity means that principal rays (the rays passing the centre of the pupil), for example 212, 214 and 216 in Figure 2, are parallel with the optical axis at the entrance slit and spectrum plane. In this condition, it can be shown that the radial distances of points in the slit and spectrum image from the optical axis are proportional to the sines of the angles which the associated principle rays make with the optical axis at the grating, for each radiation wavelength. This is exactly the condition required to correct for distortion in the spectrum image generated at the grating.

The optical system therefore gives very little curvature of the image of straight structure in the object plane formed at the spectrum plane, and very little curvature of spectrum lines associated with individual points in the object plane.

Figure 4 shows an alternative form of the apparatus shown in Figures 2 and 3. The refracting corrector 104 now includes a reflecting prism 400, which has flat

surfaces. The main function of the prism is to fold the optical path within the refractive corrector, in order to separate the object plane 102 from the spectrum plane 112. This arrangement is more convenient, separating the detector located at the spectrum plane, which may be a CCD area array or other TV camera device, from the optics forming an image of a target area onto the object plane.

A small amount of spherical and axial chromatic aberration is introduced by finite free-space paths between the object plane 102 and the corrector 104, and between the corrector and the spectrum image plane 112. Primary correction is perfect using a homogeneous corrector only if the object plane and spectrum plane are in contact with the corrector, which is often inconvenient in practice, at least for the spectrum plane at which a detection system must operate.

Some improvements can be achieved by using a different material for part of the refractive corrector, for example the prism 400. Spherical aberration correction is improved by using a material of higher refractive index for the prism than for the rest of the corrector, and axial chromatic aberration correction is improved by using a material of higher dispersion.

The refractive corrector 104 shown in Figure 4 also includes a blocking filter 402. The filter removes short wavelength radiation diffracted at high orders onto area of the spectrum where longer wavelengths, diffracted at lower orders, are to be recorded.

For use in the spectral region from near ultra-violet to near infrared, the filter, 402, will typically be a

glass doped to absorb radiation of short wavelengths and transmit longer wavelengths. The filter, 402, may be cemented into the refracting corrector.

A wedge of filter glass may be used as indicated in Figure 4, with the apex 404 of the wedge opposite a region of the spectrum nominally transmitted by the filter, 402, but unaffected by high order diffraction of short wavelength radiation. The thicker part of the filter, 402, is located opposite regions of the spectrum assigned to longer wavelength radiation. For these areas of the spectrum, the filter will remove short wavelength radiation diffracted at high orders.

Use of a wedge minimises the effect of the edge of the filter, which is opposite useful area of the spectrum plane, on the quality of the spectrum image. The refractive corrector material to which the filter is cemented will preferably be index matched to the filter material in order further to reduce the effect of the filter on spectrum image quality.

Stray radiation which follows unwanted paths from the entrance slit to the spectrum plane, would produce errors in measurements made on radiation reaching the spectrum plane. Stray radiation paths are produced by scatter at optical surfaces, by Fresnel reflections from refracting optical elements, and by ghost images from diffraction gratings.

Stray radiation is generally well controlled in the present apparatus described above. The system has very few surfaces capable of contributing to scatter, or stray Fresnel reflections. The first Fresnel reflection from the spherical surface will return to

the spectrum plane at the position assigned to zero-order diffraction - always outside the useful spectrum area.

However, there is a special problem, common with other imaging spectrometers, of reflections from the detector system located at the spectrum plane, which is typically a TV camera target with a highly reflecting surface. Radiation reflected from the detector surface is generally directed back to the grating, and, in one of the diffraction orders, returns from the grating to the detector.

The severity of this stray radiation problem can be limited by arranging that the grating diffraction from the useful spectrum area back to the same area is inefficient. Typically, the entrance aperture will be located near the optical axis and the used spectrum will be formed off axis. If a slit-shaped entrance aperture is at the optical axis, then the stray radiation returning to the spectrum from the grating will be a fairly well-resolved ghost image of the spectrum, formed at unit magnification, with no relative shift of wavelengths, but with entrance aperture images reversed about the plane of symmetry. The effect of this ghost can be removed by relatively simple signal processing.

Alternatively, the stray radiation path due to reflection between the detector surface and the grating can be eliminated by operating the system in an off-axis section of the optical aperture. The radiation may be input such that it falls on an area of the grating which is entirely on one side of a plane through the optical axis. The reflection from the

detector surface will be directed to the area, at the grating station, on the other side of the plane, where there may be no grating area or the grating may be masked off.

Figure 5 shows an alternative configuration according to the invention, in which the corrector means, is a spherical mirror 304 rather than a refracting block 104.

The spherical mirror corrector 304 is used with a spherical reflecting diffraction grating 306. The surfaces of the mirror 304 and the grating 306 are concentric, with a common centre of curvature at N3. The grating rulings are equispaced, straight and parallel, in this projection, with the entrance slit 302. The entrance slit 302 is placed in the plane orthogonal to the optical axis 310 which also includes the centre of curvature N3. In this case the used surface of the diffraction grating 306 is convex, while the mirror corrector 304 is concave.

The radius of curvature Rc of the mirror corrector 304 and the radius of curvature Rg of the diffraction grating 306 are related approximately by the formula:

$$Rc = 2.Rg$$

There is a correspondence between this formula and that given for the refracting corrector (n.Rc = (n-1).Rg). Conventionally, in lens design work, the refractive index of the medium changes sign after reflection, so that n takes the value -1 for the mirror case (if the medium is air or vacuum).

As before, radiation leaving the entrance slit 302 diverges to fall on the spherical surface of the corrector mirror 304. In the mirror system, the entrance slit 302 must be laterally displaced from the common centre of curvature N3, so that the radiation can pass the grating 306 in its path from the entrance slit 302 to the surface of the mirror 304.

The radiation is reflected from the corrector mirror surface in a converging beam, and falls on the convex surface of the diffraction getting 306. The radiation is reflected and diffracted from the grating 306 in a diverging beam, which falls again on the corrector mirror surface. The mirror 304 reflects the radiation into a converging beam which passes the diffraction grating 306 and reaches a spectrum image focus 312 in the plane P orthogonal to the optical axis 310 which includes the common centre of curvature N3 and the entrance slit 302.

A detector, for example an area array detector, may be placed at the spectrum image 312.

This embodiment of the invention, like the refracting versions, gives a primary correction for all aberrations of the spectrum image. The slit at the focus 312 is imaged 302 as a straight line in the plane 312 in each wavelength of the radiation, if the entrance slit 302 is itself straight, and these image lines associated with different wavelengths are parallel. The line spectrum of each point in the entrance slit is imaged at 312 as a straight line, and these lines area also parallel.

The mirror corrector arrangement is less compact than

those in which a refracting corrector is used, and the higher order aberrations of the spectrum image will often be more severe, due to the necessary separation between the entrance slit 302 and the centre of curvature N3. However, the arrangement remains well corrected by comparison with arrangements using only curved diffraction gratings. It is particularly useful in imaging spectrometers working in radiation for which refracting materials are inconvenient, for example in ultraviolet radiation.

In arrangements according to the invention, it will generally be convenient to use reflecting diffraction gratings provided on the side of the substrate material from which radiation arrives, as indicated in Figures 1 to 4. It is sometimes beneficial, however, to provide imaging spectrometer systems according to the invention in which the diffraction grating is produced on the rear surface of a concentric meniscus substrate, as indicated in Figure 6.

In this diagram, the corrector means 404 is again shown as a refracting block, with a spherical face 407 having a centre of curvature M3. The diffraction grating 406 is formed on the convex surface 420 of a meniscus 421, in which the centres of curvature of both the convex surface 420 and the inner concave surface 422 are at M3. Radiation passes through the concave surface 422 in its path from an entrance slit 402 to the diffraction grating surface 406, and the reflected diffracted beam again passes through surface 422 in its path to the spectrum image 412. The entrance slit 402 and the spectrum plane 412 are in or close to the plane orthogonal to the optical axis 410, which passes through the common centre of the curvature M3. The

grating rulings are straight, equispaced and parallel in the projection on a plane orthogonal to the optical axis, and also preferably parallel in this projection to the entrance slit 402.

In this case the relationship between the radii of curvature of the three spherical surfaces which gives a primary correction for all aberrations of the spectrum image is given by the equation:

$$\frac{n-1}{n.Rc} = \frac{n'-1}{n'} \quad \frac{1}{Ri} - \frac{1}{Rg} + \frac{1}{Rg}$$

Where Rc is the radius of the corrector surface 407, Ri is the radius of the concave surface 422 of the grating substrate, Rg is the radius of the grating surface 406, n is the refractive index of the corrector 404, and n' is the refractive index of the substate of the meniscus 421.

Unless the thickness Rg-Ri of the meniscus 421 is large compared with the radii, there is only a small change in the optimum ratio of grating and corrector radii.

This arrangement can be used to protect the grating surface. It also has value in some practical arrangements in increasing the wavelength at which the grating surface provides peak diffraction efficiency.

One application of the apparatus is in spectroscopic mapping of the Earth surface from an orbiting satellite, in which motion of the satellite, except in geostationary orbit, provides a mechanism for scanning a slit-shaped aperture of the imaging spectrometer to

cover a swath of Earth surface in sequential line samples.

The apparatus may also be used in spectroscopic imaging of Earth surface from civil and military aircraft, for example in plotting paths of submarines.

Other applications in imaging spectroscopy include thin layer chromatography, photobiology, visual display analysis, food analysis, microscopic specimen analysis, and a wide range of production control and surface inspection applications, including for example control of paper and textile colours and inspection of banknotes and other patterned products.

In generaly it will be necessary for the apparatus in which the spectrometer is used to include a lens or other imaging system to focus an image of the object surface onto the spectrometer object plane. In many applications, the target surface to be measured is moving, and the movement can be used to scan the instantaneously sampled area to cover a target surface. In other applications, the instrument will include a scanning system between the object surface and the spectrometer to move an image of the target surface across the entrance aperture. The scanning system may for example be a mirror rotated on a galvanometer.

In addition to imaging spectroscopic applications, in which spatial as well as spectral analysis is required, the spectrometer design described above can be used in the less demanding spectroscopic applications in which only a spatially averaged spectral distribution is to be measured.

CLAIMS

1. A spectrometer comprising an object plane (102), corrector means (104), a curved reflecting grating (106), and an image plane (112), whereby radiation from the object plane (102) passes to the corrector means (104), and from the corrector means (104) to the curved reflecting grating (106), is reflected therefrom to the corrector means (104), and passes from the corrector means (104) to the image plane (112).

2. A spectrometer as claimed in claim 1 characterised in that the curved reflecting grating (106) is a concave reflecting grating (106).

3. A spectrometer as claimed in claim 1 characterised in that the curved reflecting grating (106) comprises a convex reflecting grating (106).

4. A spectrometer as claimed in claim 1 or 2 characterised in that the corrector means (104) comprises a transparent block through which the radiation passes.

5. A spectrometer as claimed in claim 4 characterised in that the transparent block (104) has an input face (204) for receiving radiation from the object plane (102), and an output face (206) for passing radiation from the corrector means (104) to the concave reflecting grating (106).

6. A spectrometer as claimed in claim 5 characterised in that one of said input or output faces is flat and the other of said faces is curved.

7. A spectrometer as claimed in claim 6 characterised in that said input face (204) is flat and said output face (206) is curved.

8. A spectrometer as claimed in 6 or 7 characterised in that the curved reflecting grating (106) is provided on a surface of a medium, the radiation passing to the curved reflecting grating and being reflected therefrom without passing through that medium.

9. A spectrometer as claimed in claim 8 characterised in that the curved surfaces of the corrector means (104) and the concave reflecting grating (106) are spherical, and the radius of curvature R_C of the spherical surface of the corrector means (104) and the radius of curvature R_G of the spherical surface of the concave reflecting grating are approximately related by the formula

$$n.Rc = (n-1).Rg$$

wherein n is the refractive index of the material of the corrector means (104).

10. A spectrometer as claimed in claim 6 or 7 characterised in that the curved reflecting grating (106) is provided on the surface of a meniscus of material transparent to said radiation, the radiation from the corrector means (104) passing to the curved reflecting grating (106) through the medium of the curved meniscus, and being reflected back through the material of the curved meniscus to the corrector means (104).

11. A spectrometer as claimed in claim 10 characterised in that the curved surfaces of the corrector means (104), and of the meniscus, including the curved reflecting grating (106) are spherical, and the radius of curvature R_c of the spherical surface of the corrector means (104), the radius of curvature R_G of the spherical surface of the concave reflecting grating (106), and the radius of curvature R_I of the concave surface of the meniscus remote from the surface carrying the reflecting grating (106), are approximately related by the formula

$$\frac{n-1}{n.R_c} = \frac{n'-1}{n'} \cdot \left(\frac{1}{R_I} - \frac{1}{R_G}\right) + \frac{1}{R_G}$$

wherein n is the refractive index of the material of the corrector means (104), and n' is the refractive index of the material of the meniscus.

12. A spectrometer as claimed in claim 3 characterised in that the corrector means (104) comprises a spherical mirror.

13. A spectrometer as claimed in claim 12 characterised in that the surfaces of the corrector means, the spherical mirror and the convex reflecting grating (106) are concentric.

14. A spectrometer as claimed in claim 13 characterised in that the radius of curvature R_c of the corrector means, spherical mirror and the radius of curvature R_G of the spherical surface of the convex reflecting grating (106) are related approximately by the formula

$$R_C = 2.R_G$$

15. A spectrometer as claimed in any of claims 1 to 14 characterised in that the object plane (102) includes an entrance aperture in the form of a slit.

16. A spectrometer as claimed in any of claims 1 to 15 characterised in that a radiation detector in the form of a CCD area array is mounted at said image plane (112).

17. A spectrometer as claimed in any of claims 1 to 16 characterised in that there is provided an input lens (108) for focusing a remote image onto the object plane (102).

18. A spectrometer as claimed in claim 1 characterised in that a refractive corrector (400) is provided between the object plane (102) and the corrector means (104).

19. A spectrometer as claimed in claim 18 characterised in that the refractive corrector 400 has a higher refractive index and higher dispersion than the corrector means (104).

20. A spectrometer as claimed in claim 18 or 19 characterised in that there is provided a blocking filter (402).

Fig. 1.

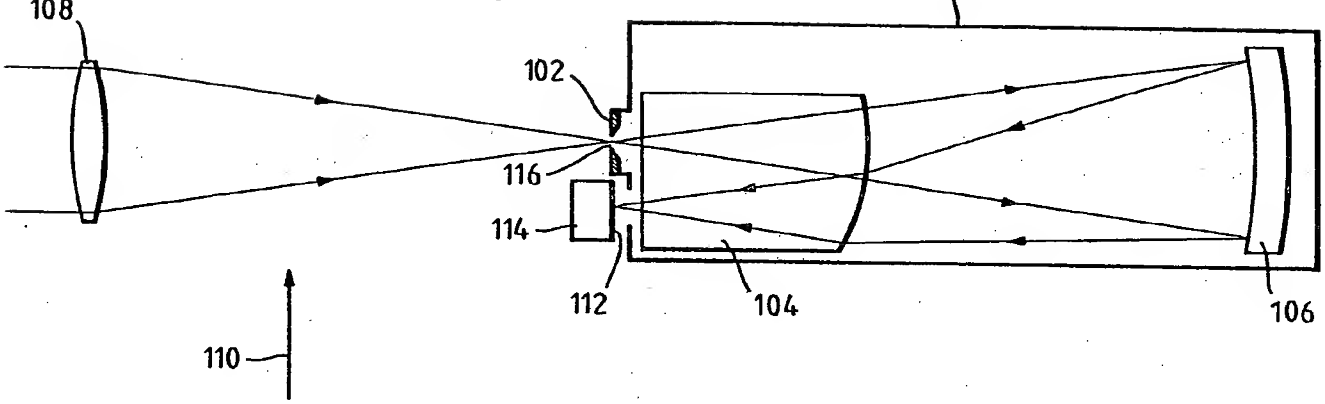

100
108
102
116
114
112
104
106
110

Fig. 2.

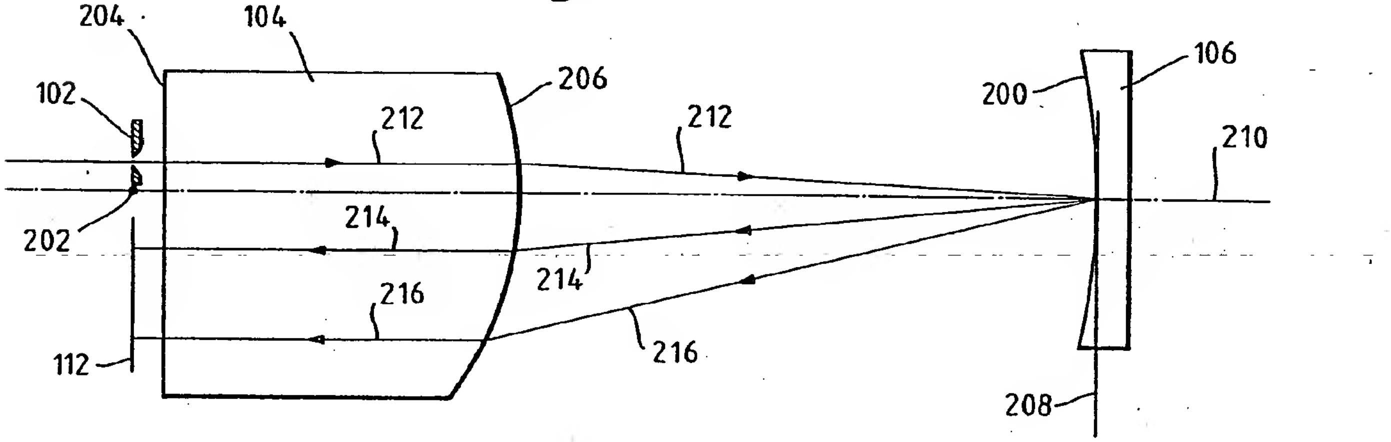

204
104
102
206
212
212
200
106
210
202
214
214
216
216
112
208

Fig. 3.

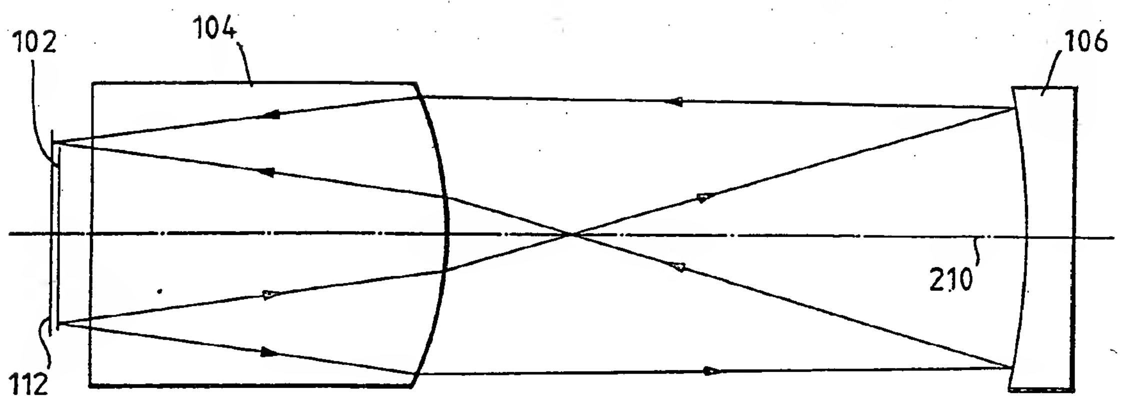


Fig. 4.

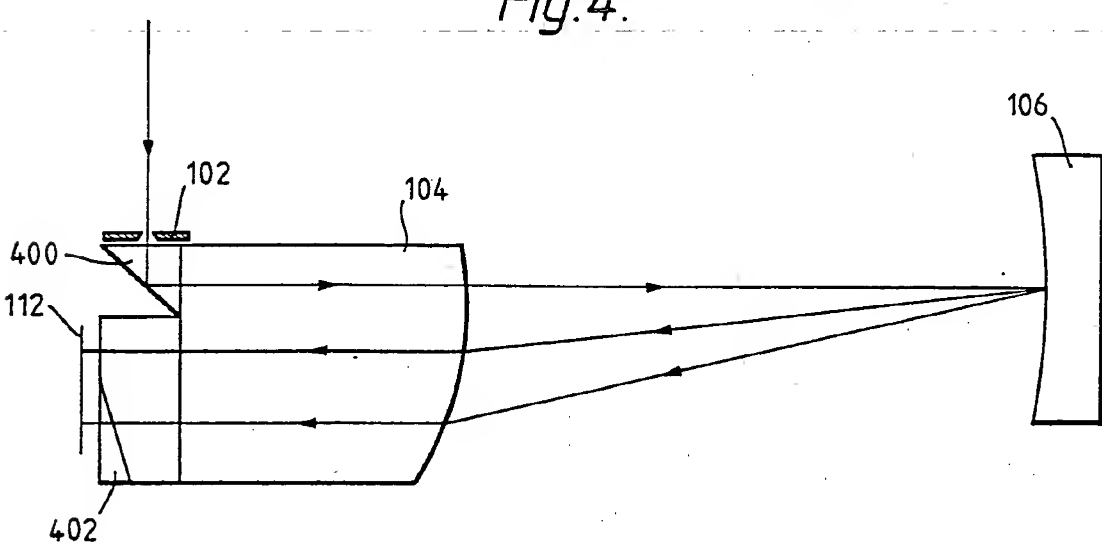


Fig. 5.

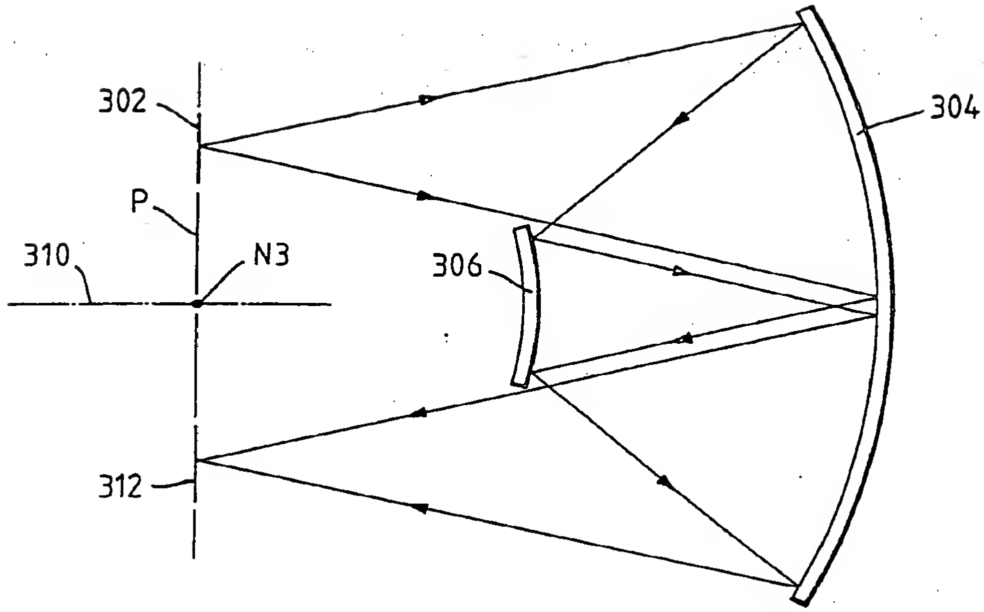
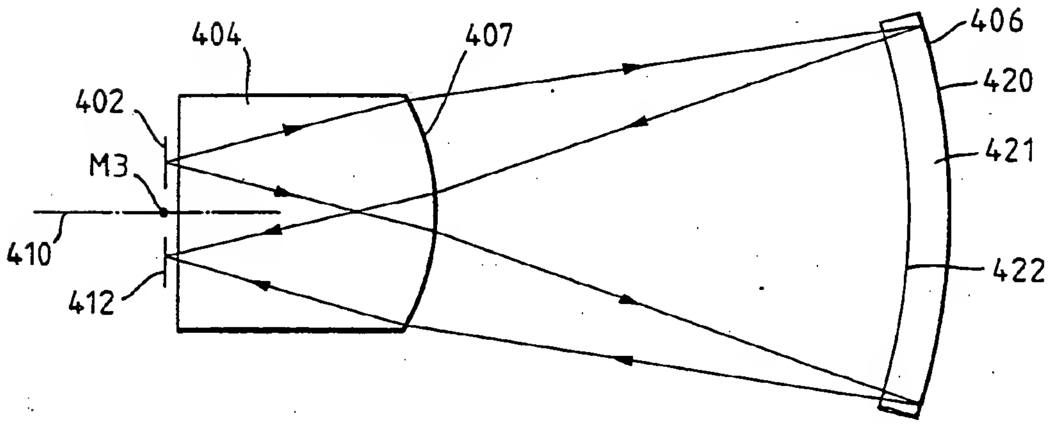


Fig. 6.



INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 89/01035

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC[5]: G 01 J 3/18

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC[5]	G 01 J 3/18, G 01 J 3/28, G 01 J 3/00, G 02 B 6/34

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	Review of Scientific Instruments, vol. 45, no. 11, November 1974 American Institute of Physics (US) G.A.H. Walker et al.: "A compact multichannel spectrometer for field use", pages 1349-1352, see part II. "Optics and Frame"; pages 1349-1350 --	1,2,4,5,15, 17
A	Patents Abstracts of Japan, vol. 7, no. 59 (P-179)(1196), 26 February 1983, & JP, A, 57198423 (NIHON ITA GLASS KK) 6 December 1982, see abstract --	1,6
A	Patents Abstracts of Japan, vol. 5, no. 118 (P-73)(790), 30 July 1981, & JP, A, 5660401 (NIPPON DENSHIN DENWA) 25 May 1981, see abstract --	1
A	IEEE Transactions on Geoscience and Remote Sensing, vol. GE-22, no. 6, November 1984 (New York, US) G. Vane et al.: "Airborne imaging spectrometer: a new tool for remote sensing"	1

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
14th December 1989	26 01. 90
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	T.K. WILLIS

Form PCT/ISA/210 (second sheet) (January 1985)

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
	pages 546-549, see pages 546,547 down to "reaching the detector"	